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by

Henrich Henriksen

June 1996

Technical Report

Funding was provided by the Office of Naval Research through
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George V. Frisk, Chair
Department of Applied Ocean Physics and Engineering

Typical Power Budget and Possible Energy Source For Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE)

By Henrich Henriksen

The AOSN LSE (Ref. 1) will be held in the Labrador Sea at a seawater depth of 3000 - 3500 meters. The total system will consist of a number of AUVs which will operate from a set of moorings within a defined area. The AUVs will navigate within the defined area by using acoustic transponders on the moorings. Each mooring will be placed on the seafloor (ca 3000 meters). The docking stations will be placed in the water column at 1000 - 2000 meters water depth. Each AUV will have at least one possible docking station to charge batteries and to transfer data.

This memo will show two different load pattern examples (Case A and B) for the AOSN LSE, and the implications upon the power budget of the mooring. There are many uncertainties in the input numbers, but most of the power budget appears to be reasonable. The total duration of the experiment in both Cases (A and B) is set to 8 months. The experiment will be split into a number of events in which high AUV activity is required. The events are defined in duration, but they will not be as regular as modeled in this report. During each event the AUVs leave the moorings and go on missions. The time between the missions is the charging time. Some of the variables will be defined in order to work out the power usage. Some of the power users are known and measured, others will be qualified guesses. All of the choices are made so that the total system appears as easy and redundant as possible. This might reduce the performance of the system.

In the second part, the possible use of a seawater battery and its implications upon the system will be discussed. A preliminary design of the sizes and weights of a seawater battery for this application is also included. All the essential data is presented in tables and graphs as well as all the calculations which are in Appendix 1 and 2 as MathCad documents.

The power usage discussed later in this report will focus on the mooring, and not on the AUVs.

AUVs and moorings power usage

The total number of AUVs is put to 6 and they are dispersed to 3 moorings with two docking stations on each mooring. This means that there are no spare charging or data transfer stations. Each mooring might also accommodate one AUV extra on passive docking. This would make it possible to run six AUVs (at a certain duty cycle) from two moorings in the event that one mooring fails.

Power users on the Odyssey

The power usage on the Odyssey consists of three major components. The largest is the power required to drive the vehicle through the water. This is mainly a function of the vehicle speed (power/cubed). The drag power is set to ca 80 watts at a cruising speed of 1.4 m/sec and a Cd=0.08 (mechanical efficiency of 40%).

The second component is the acoustic modem. The power usage will be in the order of 20 watts and the modem is set to be on at all time during one event. The Odyssey is also using some energy during data transfer while docked, dominated by the acoustic modem. The duration of this data transfer is put to 50% of the event time and must occur during the time between two events.

The third user is the hotel load which consists of units like sensors and data storage. This is assumed to be in the order of 60 watts. In this report, the total power usage of one Odyssey during a mission is in the order of 160 watts.

Power users on the mooring

The main power usage on the mooring is for acoustic communication, computing and data storage. The acoustic modem (20 watts) on the mooring will be used during each event plus 50% of the duration of one event. The rest of the power users at the mooring are put to 10 watts on average, without large peaks. The energy required to do the satellite transfer is small and it will not be more than 3 kWhr over the entire experiment.

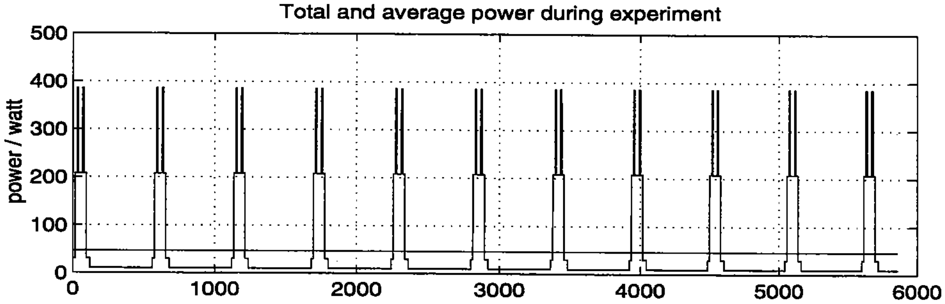
Duration and duty cycles

The following examples will be separated into A and B. In both cases, the total experiment duration will be put to 8 months.

	Case A	**Case B**
Number of AUVs	6	6
Number of moorings	3	3
Total experiment duration	8 months	8 months
Maximum duration of event	72 hours	80 hours
Time between events	20 days	20 days
Minimum charging time	16 hours	24 hours
Maximum mission time	8 hours	16 hours
AUV cruising speed	1.4 m/sec	1.4 m/sec
Number of events	11	11
Number of missions/event	3	2

In the graphs that follow (Fig. 1 and 2), the power usage of the *Mooring* is plotted against time. This means that the lower level is symbolizing the power usage at the mooring when the AUVs are sleeping. The graph for Case B (Fig. 1) is labeled with AUV 1 and AUV 2 when they are on mission (away from the mooring). The event starts and AUV 1 goes on mission (event starts at time equal zero on both plots), AUV 1 returns, it starts to charge it's batteries and AUV 2 goes on mission. This means that it is at maximum, one AUV from each mooring on mission during one event. The peaks occur when both AUVs are charging their batteries at the same time. The high level of power usage after each event is the mooring modem under data transfer. The first graphs shoves the full 8 months (in hours) of the experiment duration and the peaks are the events which are distributed evenly. The second graphs of each case show an expanded view of one event.

Fig 1. This gives a duty cycle for Case B:



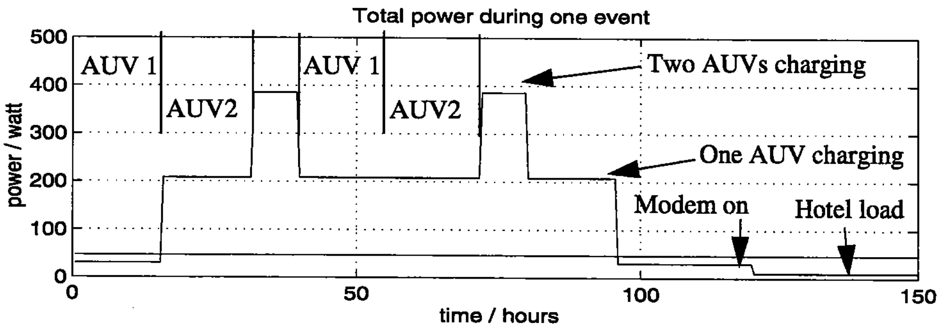
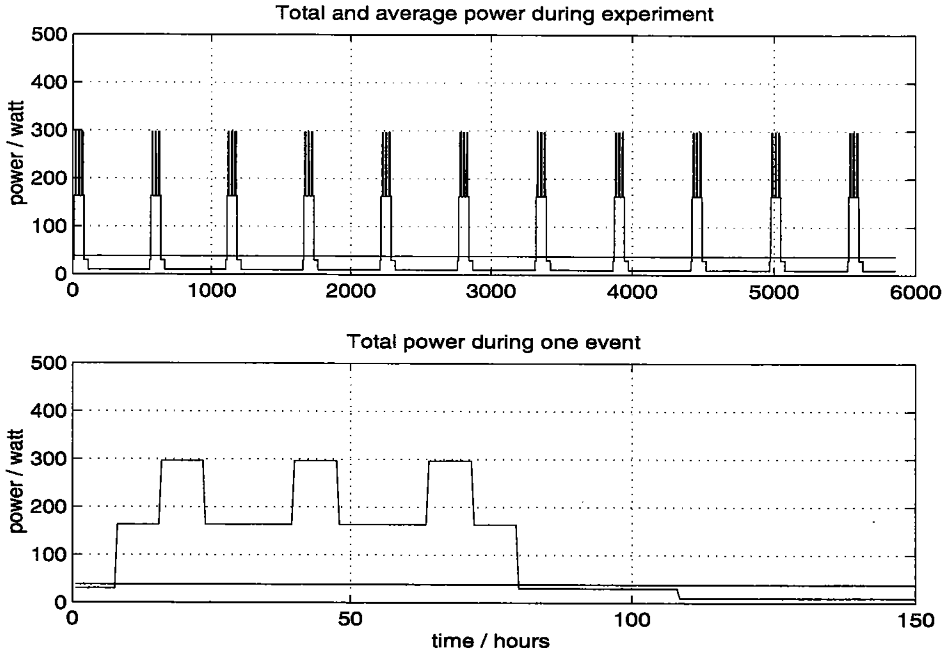


Fig 2. This gives a duty cycle for Case A:



Values for each mooring:

(2 AUVs)

	Case A	Case B
Average power at mooring	47 watts	56 watts
Total energy needed for mooring	256 kWhr	304 kWhr
Maximum peak power	296 watts	385 watts
Energy needed during one event	14.9 kWhr	19.2 kWhr

Values for the total experiment:

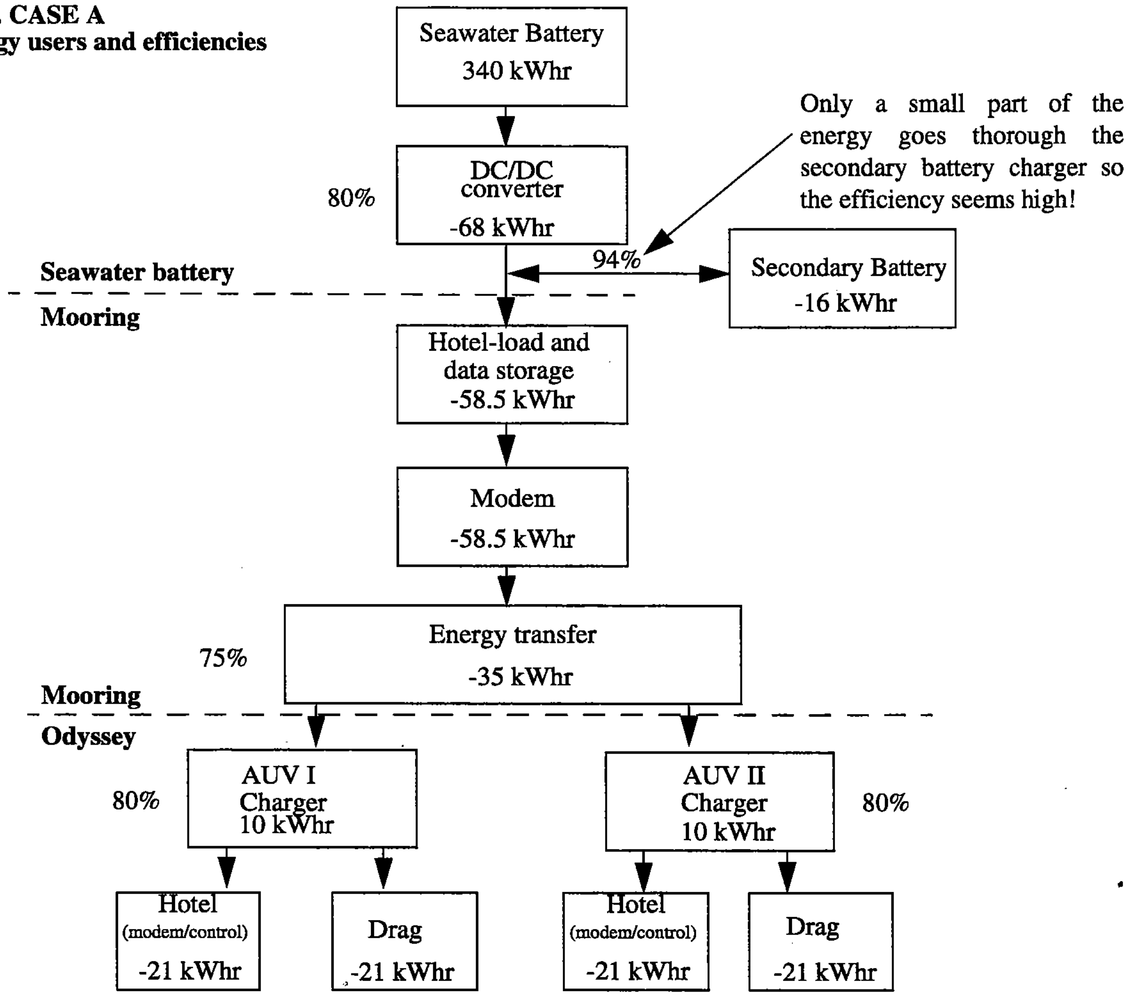
(6 AUVs and 3 moorings)

	Case A	Case B
Minimum number of AUVs in the water during one event	2	2.4
Size of AUV batteries	1.3 kWhr	2.6 kWhr
AUV hours during one event	48 hrs	64 hrs
AUV distance traveled during event	242 km	322 km
Total AUV hours (experiment)	528 hrs	704 hrs
AUV distance traveled during experiment	2661 km	3542 km

Efficiencies

In the calculations above, the following efficiencies have been used: All charger efficiencies are put to 80%, energy transfers from mooring to AUV are put to 75%. The propulsion efficiency of the Odyssey is put to 40%, and it is used a Cd = 0.08 (based on frontal area). Later in this report the DC/DC converter of the seawater battery is put to 80%.

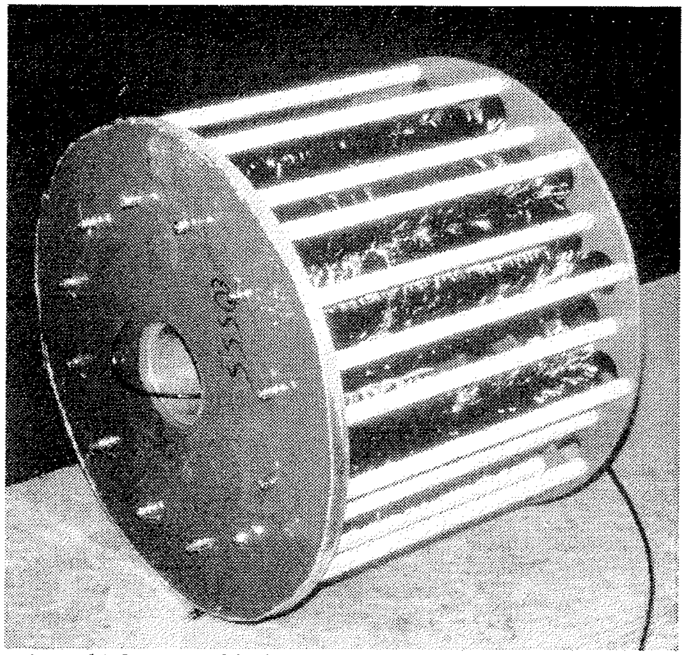
Fig 3. CASE A
Energy users and efficiencies



NDRE (Norwegian Defence Research Establishment) Seawater Battery

The Seawater cell developed at NDRE is a power source intended for powering stationary equipment in deep waters. The cell uses anodes made from commercial magnesium alloys, seawater as the electrolyte, and oxygen dissolved in the seawater as oxidant. The cathode is made of carbon fibers. Typical figures of merit from prototype cells are 4 watts over 6 months with a specific energy density of 800-1000 wh/kg based on dry weight, and a volumetric energy density of 125 Wh/liter (Ref. 2, Fig. 4). The seawater battery delivers a cell voltage of 1.2 - 1.6 volts, because of the nature of the battery, it is impossible to connect the batteries in series (short circuit). It is, therefore, necessary to use a DC/DC converter. In all the calculations below there have been used a DC/DC efficiency of 80%.

Fig 4. Prototype of a Seawater battery cell



The seawater cell configuration which is suitable for AOSN LSE is based upon this half meter long prototype (Ref 2).

Environmental conditions

To ensure the transport of oxygen to the surface of the cathode there are many considerations. The surface area of the exposed cathode surface must be as large as possible. This means that a large cross section of the cell facing towards the seawater current is desirable. The average and minimum sea current at the location is important. The seawater battery requires above 5 cm/sec as average (this is a "High power cell"). Also, the oxygen content of the seawater is important. A content of 0.3 mole/m^3 is more than enough (the relevant environmental data is in Appendix 3). The environmental conditions in the Labrador Sea varies but the basic feature of the area seems to be good mixing between the layers; a typical site (Appendix 4) has a close to constant oxygen content through the water column.

When a seawater battery is deployed it must not be shielded by any structure. It is also important to place it at a distance (2-5 meters) from the seafloor to ensure seawater flow through the battery.

It is worth noting that when using a seawater cell, it is important to remember the nature of the cell. A contact between any metallic part (except titanium) and the cathode of the cell will result in rapid galvanic corrosion. This means that the user must make sure that the cell is insulated from any metallic part of the mooring structure.

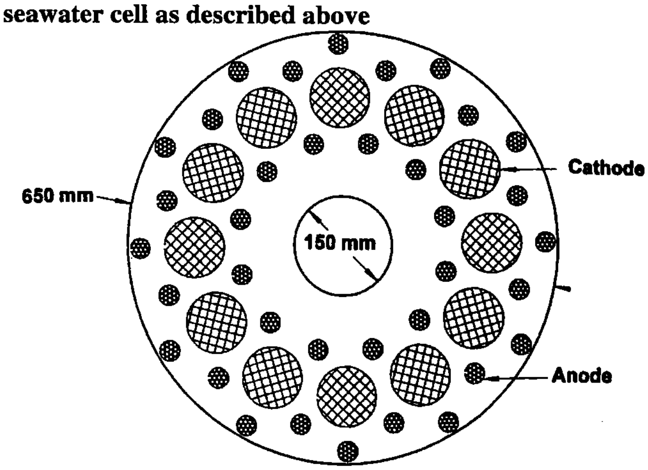
Size and weight of a Seawater Battery for use with AOSN

All the numbers presented here are crude estimates. The cell structure used is based upon prototypes which NDRE has developed over the past four years.

The seawater battery can be dimensioned by two different criteria: power requirements or long-term energy requirements. The difference with regards to an application like AOSN is typically the use of a secondary battery, and also the total volume of the battery. A battery dimensioned only to maintain the average power requirements must have a fairly large secondary cell to deliver power during events. The weight of a seawater battery is mainly a function of the energy content (the mass of magnesium), and will be nearly constant in an application like AOSN. The total volume of the seawater battery is mainly a function of the power requirements.

The seawater batteries in the tables below are built up by cylindrical cells of 0.6 meters in diameter and 1 meter height (double length of the cell in Fig. 4). The cells can be suited with one DC/DC converter each (placed in the middle) and the DC/DC converter output can then be connected in parallel. This will ensure a redundant system in the case of a failure in one of the DC/DC converters. It is also desirable (because of the low cell voltage and high currents) not to have a long distance between the DC/DC converter and the cells.

Fig 5. Cross section of a seawater cell as described above



For each of the Cases (A and B) it has been calculated a size of battery using the same configurations (Fig. 5), but two different anode diameters (22 mm and 32 mm). This shows different possibilities with regards to dimensioning. The anode diameters are commercially available sizes. Each of the cells can deliver a maximum of 8 watts and the energy content of one cell is either 24 kWhr (22 mm anode) or 51 kWhr (32 mm anode). These values are taken after the DC/DC converter but before the loss to a secondary battery. If the power users are assumed to be larger or smaller than the examples in case A or B the seawater battery can be scaled using these cell units.

	Case A		**Case B**	
	22 mm	**32 mm**	**22 mm**	**32 mm**
Energy content (before secondary)	288 kWhr	307 kWhr	336 kWhr	358 kWhr
Maximum power	77 watts	48 watts	112 watts	56 watts
Number of cells	12	6	14	7
Weight in Air (including DC/DC)	369 kg	350 kg	431 kg	409 kg
Weight in water (approx)	185 kg	175 kg	216 kg	205 kg
Total volume	3393 l	1696 l	3958 l	1979 l
Specific energy (in air)	780 Whr/kg	877 Whr/kg	780 Whr/kg	877 Whr/kg
Energy density	85 Whr/l	181 Whr/l	85 Whr/l	181 Whr/liter
Secondary battery	9.5 kWhr	12.2 kWhr	12.75 kWhr	16.0 kWhr

The variance of the secondary battery size with regards to number of missions at each event, for each of these cases, is plotted at the end of the MathCad documents in the Appendix.

The table below shows how fast it is possible to use the battery and how many events the cell can accommodate in such an application when the rest of the system is as defined above.

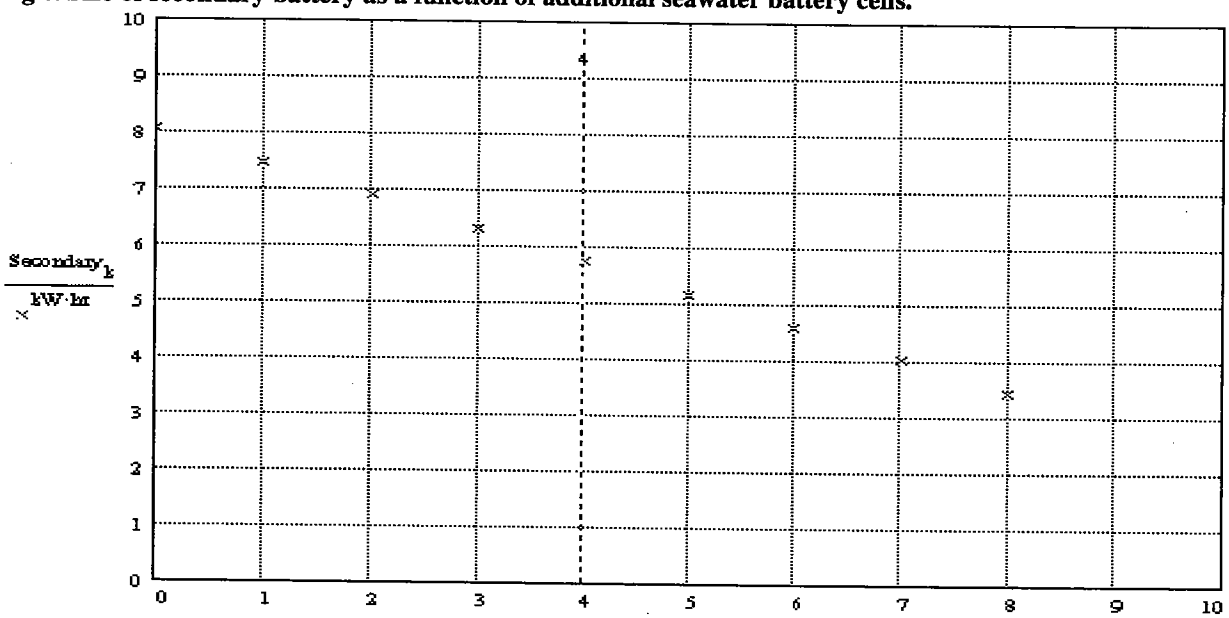
	Case A		**Case B**	
	22 mm	**32 mm**	**22 mm**	**32 mm**
Min. experiment duration	125 days	245 days	125 days	245 days
Max. number of events	16	11	14	11
Time between events	5 days	20 days	6 days	20 days

This means that the design of a battery which can deliver an excess of power makes the system more flexible and a *shorter duration between each event is possible.*

The secondary battery and the DC/DC converters

The AOSN LSE seawater battery will almost certainly require a secondary battery. The size of a typical cell is in the order of 10 - 15 kWhr. This is a cell which is 4-10 times larger than a typical Odyssey battery. It may be beneficial to use the same battery technology on both the mooring and the Odyssey.

Fig 6. Size of secondary battery as a function of additional seawater battery cells.



Number of additional seawater battery cells

The graph above (Fig. 6) shows how the size of a secondary battery will go down with each additional seawater battery cell. (This example is Case A with 22 mm anodes; four cells has an approximate volume of 1000 liter)

Recharging of seawater batteries

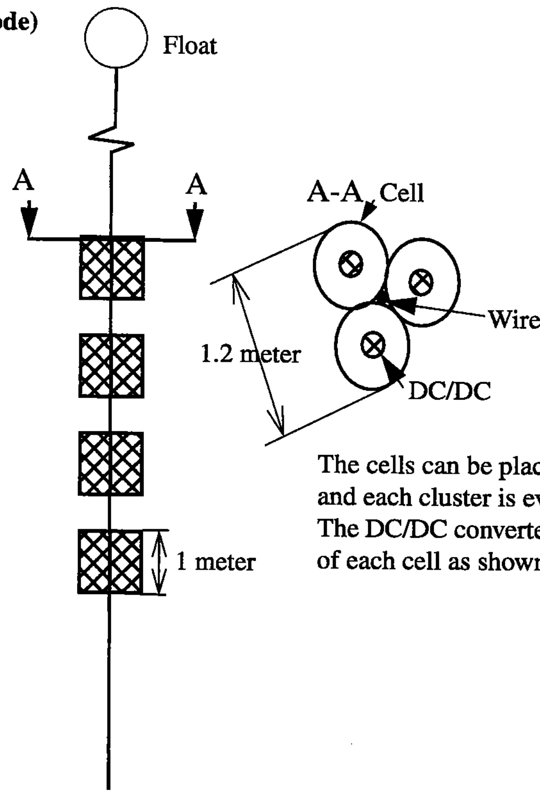
The seawater batteries, like the ones described above, can be reused a number of times (>5) by replacing the anodes and possibly the cathodes. This process is not expensive or difficult. The most expensive parts are the cathodes (which must be delivered by Simrad), and the labor. The magnesium costs in the order of $10/kg (typically 300 kg for Case A) plus the cost of machining each anode (simple process).

Advantages and disadvantages with using seawater battery

The main advantage of using a seawater battery is that there are no requirements of a large pressure vessel to accommodate the energy source. The secondary battery can be either a pressure compensated unit or it might require a pressure housing. The DC/DC converters and the charger will need a small pressure housing. The use of several DC/DC converters connected in parallel makes the system redundant. The seawater battery consists of no moving parts and does not contain any dangerous components either for the environment or people.

The battery has a low weight and high energy density both on land (800 Whr/kg) and in the water. This simplifies the handling and reduces the need for buoyancy. Although the battery is large in volume it can be dispersed out on the mooring wire (Fig. 7) in such a way that it should be possible to handle without difficulty. The battery is fairly robust.

Fig 7. Case A (22mm anode)
12 cells in four clusters
(not to scale)



The cells can be placed in clusters of three cells and each cluster is evenly spaced along the wire. The DC/DC converters can replaced in the middle of each cell as shown on the drawing above.

The main disadvantages are a large volume and a low power rate.

Conclusion

The energy usage on the mooring will be in the order of 250 - 500 KWhr, depending on number of sensors, number of AUVs on each mooring and the energy required to do data handling.

There are several types of power sources that can deliver 250 - 500 KWhr, but since the most attractive ones are those with a high energy density, the most obvious alternatives are a large lithium pack or a fuel cell. The disadvantages of such systems for underwater applications are several. This would almost certainly involve a pressure housing with an internal volume of 1500 - 2500 liters. The safety aspects of such a large lithium pack are serious and also the handling of a large fuel cell can be hazardous.
A large fuel cell has several moving parts in pumps, valves and combined with a highly corrosive environment inside the cell, there are questions about the reliability of the system.

The cost of a large fuel cell or a large lithium pack are traditionally high.

Energy delivery to an experiment like the AOSN LSE with the use of a seawater battery is feasible both technically and within the time span of the AOSN project. Due to of the large water depths involved and the simplicity of the system the seawater battery seems like a good candidate. The numbers chosen for case A and B are not ideal for a seawater battery. An idealy designed system would use the energy as constantly as possible. This would be a system where the missions were distributed evenly over the total experiment, then a system without the use of secondary batteries could then be designed.

The environment of the Labrador Sea is well documented and seems suitable to accommodate a seawater battery.

The cost of energy is assumed to be lower than \$300/ kWhr, with a recharge cost lower than \$50/kWhr. (estimate).

Simrad Norway is the producer of the NDRE seawater battery. The design and development is done by Norwegian Defence Research Establishment (NDRE). A first order price of a unit such as Case A (22 mm) will be obtained from Simrad as soon as possible.

Appendix

Appendix 1	Calculations on Case A, duty cycle and alternative seawater batteries
Appendix 2	Calculations on Case B, duty cycle and alternative seawater batteries
Appendix 3	Typical environmental data from the Labrador sea

References

1) Curtin, Bellingham, Catipovic and Webb, Autonomous Oceanographic Sampling Networks' Oceanography Vol. 6, No. 3 1993

2) Hasvold, Henriksen and Syversen (NDRE) 'Improvements in the rate capability of the magnesium-dissolved oxygen seawater cell'(1995) Power Sources 15

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Calculations on Case A, duty cycle and alternative seawater batteries.
Power budget of the Autonomous Oceanographic Sampling Network Moorings

Defenitions:

$nm := 1852 \cdot m$

$km := 1000 \cdot m$

$\rho := 1028 \cdot \frac{kg}{m^3}$

$mon := \frac{1}{12} \cdot yr$

SYSTEM CONFIGURATION

Number of AUV's	$AUV := 6$	
AUV speed	$Vauv := 1.4 \cdot \frac{m}{sec}$	
Number of MOORINGS	$MOR := 3$	
Number of AUV's pr mooring	$N\_AUV\_moo := \frac{AUV}{MOR}$	$N\_AUV\_moo = 2$
Charging efficiency	$Cheff := 80 \cdot \%$	
Transfer efficiency (from mooring to AUV)	$Treff := 75 \cdot \%$	
Total time of experiment	$Time := 5846 \cdot hr$	$Time = 8 \cdot mon$
Maximum mission duration	$T\_miss := 8 \cdot hr$	
Minimum docking time	$T\_dock := 16 \cdot hr$	
Minimum time between events	$T\_rest := 20 \cdot day$	$T\_rest = 0.657 \cdot mon$
Duration of events	$T\_happ := 72 \cdot hr$	$T\_happ = 3 \cdot day$

HOTEL LOAD ON EACH MOORING $\quad Pow\_hot := 10 \cdot watt$

Total energy hotel

$Ener\_hot := Pow\_hot \cdot Time$

$Ener\_hot = 58.46 \cdot kW \cdot hr$

ACOUSTIC MODEM $\quad Aco\_mod := 20 \cdot watt$

Duty cycle modem $\quad Aco\_mod\_duty := 50 \cdot \%$

Continous power modem

$Pow\_mod := Aco\_mod \cdot Aco\_mod\_duty$

$Pow\_mod = 10 \cdot watt$

Total energy modem

$Ener\_mod := (Pow\_mod) \cdot Time$

$Ener\_mod = 58.46 \cdot kW \cdot hr$

ODESSEY

$Cd := 0.08 \quad dia := 0.6 \cdot m$

$eff := 40 \cdot \%$

$$Pow\_drag := \frac{\frac{1}{2} \cdot \rho \cdot (Vauv)^2 \cdot \left(\frac{dia}{2}\right)^2 \cdot \pi \cdot Vauv \cdot Cd}{eff}$$

$Pow\_drag = 79.757 \cdot watt$

$Pow\_instr := 80 \cdot watt$

$$Pow\_AUV := \frac{Pow\_drag + Pow\_instr}{Cheff \cdot Treff}$$

$Pow\_AUV = 266.262 \cdot watt$

Duty cycle of AUV

Total number of events

$$N\_happ := ceil\left(\frac{Time}{T\_rest + T\_happ}\right)$$

$N\_happ = 11$

Total number of missions on each happening pr AUV

$$N\_miss\_happ := ceil\left[\frac{T\_happ}{(T\_miss + T\_dock)}\right]$$

$N\_miss\_happ = 3$

Total number of missions pr AUV

$N\_missions := N\_happ \cdot N\_miss\_happ$

$N\_missions = 33$

Total energy used pr AUV

$Ener\_AUV := N\_missions \cdot T\_miss \cdot Pow\_AUV$

$Ener\_AUV = 70.293 \cdot kW \cdot hr$

Travel time pr AUV

$Tauv := N\_missions \cdot T\_miss$

$Tauv = 11 \cdot day \qquad Tauv = 264 \cdot hr$

95 kWhr of the energy goes through the secondary battery the charger efficiency for. The secondary battery is in the order of 80%. This gives a total efficiency of SBeff=94%

$SBeff := 94 \cdot \%$

TOTAL energy and average power used pr mooring

$$Power\_mooring := \frac{\frac{Ener\_AUV \cdot N\_AUV\_moo}{Time} + Pow\_mod + Pow\_hot}{SBeff}$$

Power

$$Power\_mooring = 46.86 \cdot watt$$

$$Power\_overhead := Pow\_mod + Pow\_hot$$

$$Power\_overhead = 20 \cdot watt$$

$$Energy\_mooring := Power\_mooring \cdot Time$$

Energy

$$Energy\_mooring = 273.943 \cdot kW \cdot hr$$

$$Time\_AUV := AUV \cdot N\_missions \cdot T\_miss$$

TOTAL AUV travel time

$$Time\_AUV = 66 \cdot day$$

$$Dist\_AUV := Time\_AUV \cdot Vauv$$

Total AUV traveled distance

$$Dist\_AUV = 7.983 \cdot 10^{3} \cdot km$$

Energy needed under one event

$$Ener\_happ := N\_miss\_happ \cdot T\_miss \cdot N\_AUV\_moo \cdot (Pow\_AUV) \ldots + (Pow\_hot + Aco\_mod) \cdot T\_happ$$

$$Ener\_happ = 14.9 \cdot kW \cdot hr$$

Power needed during event

$$Power\_happ := \frac{Ener\_happ}{T\_happ}$$

$$Power\_happ = 207.508 \cdot watt$$

SEAWATER BATTERY to use with AOSN case A1

All the numbers are conservative estimates.

Energy needed $\quad Energy := 280 \cdot kW \cdot hr \qquad Time := \frac{8}{12} \cdot yr$

Power needed $\quad Avg\_pow := 48 \cdot watt$

Density of magnesium $\quad r\_Mg := 1.81 \cdot \frac{kg}{liter}$

Using SSS batteries DIMENSIONS of one CELL

$height := 1 \cdot m$

$diameter := 0.6 \cdot m$

$volume := height \cdot \left(\frac{diameter}{2}\right)^2 \cdot p$

$volume = 282.743 \cdot liter$

$anod\_dia := 22 \cdot mm$

$Anod\_nr := 36$

$Cathode\_nr := 12$

Magnesium $\quad Mg\_w := \left(\frac{anod\_dia}{2}\right)^2 \cdot p \cdot height \cdot r\_Mg \cdot Anod\_nr$

$Mg\_w = 24.769 \cdot kg$

$Pot\_w := 2 \cdot kg$

Total weight of one unit $\quad Cell\_weight := Pot\_w + Mg\_w + 4 \cdot kg \qquad$ DC/DC converter weights ca 5 kg/cell

$Cell\_weight = 30.8 \cdot kg$

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

$Power\_cell := 8 \cdot (80 \cdot \%) \cdot watt \qquad$ this is from the DC/DC converter

Energy pr cell $\quad Energy\_cell := (40 \cdot kW \cdot hr) \cdot (75 \cdot \%) \cdot 80 \cdot \%$

Number of cells $\quad Cell\_nr := ceil\left[\frac{Energy}{(Energy\_cell)}\right] \qquad \frac{Energy}{Time} = 47.913 \cdot watt$

$Cell\_nr = 12 \qquad volume \cdot Cell\_nr = 3.393 \cdot m^3$

This gives :

Cathodes total number $\quad K\_n := Cell\_nr \cdot Cathode\_nr$

$K\_n = 144$

Total number of anodes $A\_n := Cell\_nr \cdot Anod\_nr$

$A\_n = 432$

$Total\_w := Cell\_weight \cdot Cell\_nr$

Total weight of system $Total\_w = 369 \cdot kg$ Weight in the water will be less than half

From DC/DC $Total\_energy := Energy\_cell \cdot Cell\_nr$

Total energy of battery $Total\_energy = 288 \cdot kW \cdot hr$

$$Energy\_density := \frac{Total\_energy}{Total\_w}$$

Energy density $Energy\_density = 0.78 \cdot \frac{kW \cdot hr}{kg}$ in air energy to the user

$Total\_volume := volume \cdot Cell\_nr$

Total volume of battery $Total\_volume = 3393 \cdot liter$

$$Volume\_density := \frac{Total\_energy}{Total\_volume}$$

Volume density $Volume\_density = 84.883 \cdot \frac{watt \cdot hr}{liter}$

Size of secondary battery is dependent uppon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

$$Power := Power\_cell \cdot Cell\_nr \qquad k := 0..10$$

$$Power = 76.8 \cdot watt$$

Overheads $P\_modem := 20 \cdot watt$

$P\_hotel := 10 \cdot watt$

AUV $P\_auv := 160 \cdot watt$

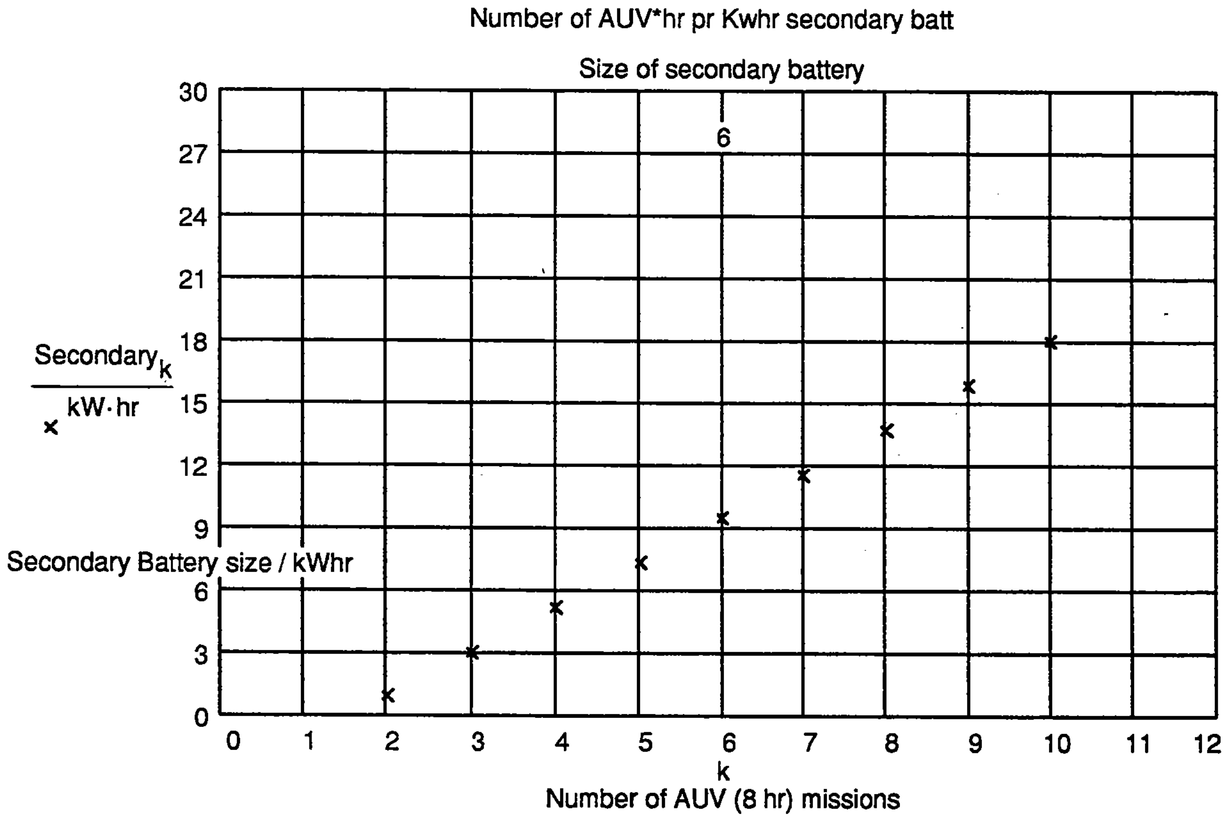
mission duration $T\_miss := 8 \cdot hr$

$A_k := T\_miss \cdot k$

event duration $Event := 72 \cdot hr$

$$Secondary_k := ((P\_modem + P\_hotel) - Power) \cdot Event + \frac{P\_auv \cdot A_k}{75 \cdot \% \cdot 80 \cdot \%}$$

Secondary battery size for case A $Secondary_6 = 9.43 \cdot kW \cdot hr$



SEAWATER BATTERY to use with AOSN Case A2
All the numbers are conservative estimates.

Energy needed $\quad Energy := 280 \cdot kW \cdot hr$ $\quad Time := \frac{8}{12} \cdot yr$

Power needed $\quad Avg\_pow := 48 \cdot watt$

Density of magnesium $\quad \rho\_Mg := 1.81 \cdot \frac{kg}{liter}$

Using SSS batteries DIMENSIONS of one CELL

$height := 1 \cdot m$

$diameter := 0.6 \cdot m$

$volume := height \cdot \left(\frac{diameter}{2}\right)^2 \cdot \pi$

$volume = 282.743 \cdot liter$

$anod\_dia := 32 \cdot mm$

$Anod\_nr := 36$

$Cathode\_nr := 12$

Magnesium $\quad Mg\_w := \left(\frac{anod\_dia}{2}\right)^2 \cdot \pi \cdot height \cdot \rho\_Mg \cdot Anod\_nr$

$Mg\_w = 52.405 \cdot kg$

$Pot\_w := 2 \cdot kg$

Total weight of one unit $\quad Cell\_weight := Pot\_w + Mg\_w + 4 \cdot kg$ $\quad$ DC/DC converter weights ca 5 kg/cell.

$Cell\_weight = 58.4 \cdot kg$

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

$Power\_cell := 8 \cdot (80 \cdot \%) \cdot watt$ $\quad$ this is from the DC/DC converter

Energy pr cell $\quad Energy\_cell := (80 \cdot kW \cdot hr) \cdot (80 \cdot \%) \cdot 80 \cdot \%$

Number of cells $\quad Cell\_nr := ceil\left[\frac{Energy}{(Energy\_cell)}\right]$ $\quad \frac{Energy}{Time} = 47.913 \cdot watt$

$Cell\_nr = 6$ $\quad volume \cdot Cell\_nr = 1.696 \cdot m^3$

This gives :

Cathodes total number $\quad K\_n := Cell\_nr \cdot Cathode\_nr$

$K\_n = 72$

Total number of anodes	$A\_n := Cell\_nr \cdot Anod\_nr$	
	$A\_n = 216$	
	$Total\_w := Cell\_weight \cdot Cell\_nr$	
Total weight of system	$Total\_w = 350 \cdot kg$	Weight in the water will be less than half
From DC/DC	$Total\_energy := Energy\_cell \cdot Cell\_nr$	
Total energy of battery	$Total\_energy = 307.2 \cdot kW \cdot hr$	
	$Energy\_density := \frac{Total\_energy}{Total\_w}$	
Energy density	$Energy\_density = 0.877 \cdot \frac{kW \cdot hr}{kg}$	in air energy to the user
	$Total\_volume := volume \cdot Cell\_nr$	
Total volume of battery	$Total\_volume = 1696 \cdot liter$	
	$Volume\_density := \frac{Total\_energy}{Total\_volume}$	
Volume density	$Volume\_density = 181.083 \cdot \frac{watt \cdot hr}{liter}$	

Size of secondary battery is dependent uppon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

$Power := Power\_cell \cdot Cell\_nr$ $\qquad k := 0..10$

$Power = 38.4 \cdot watt$

Overheads $P\_modem := 20 \cdot watt$

$P\_hotel := 10 \cdot watt$

AUV $P\_auv := 160 \cdot watt$

mission duration $T\_miss := 8 \cdot hr$

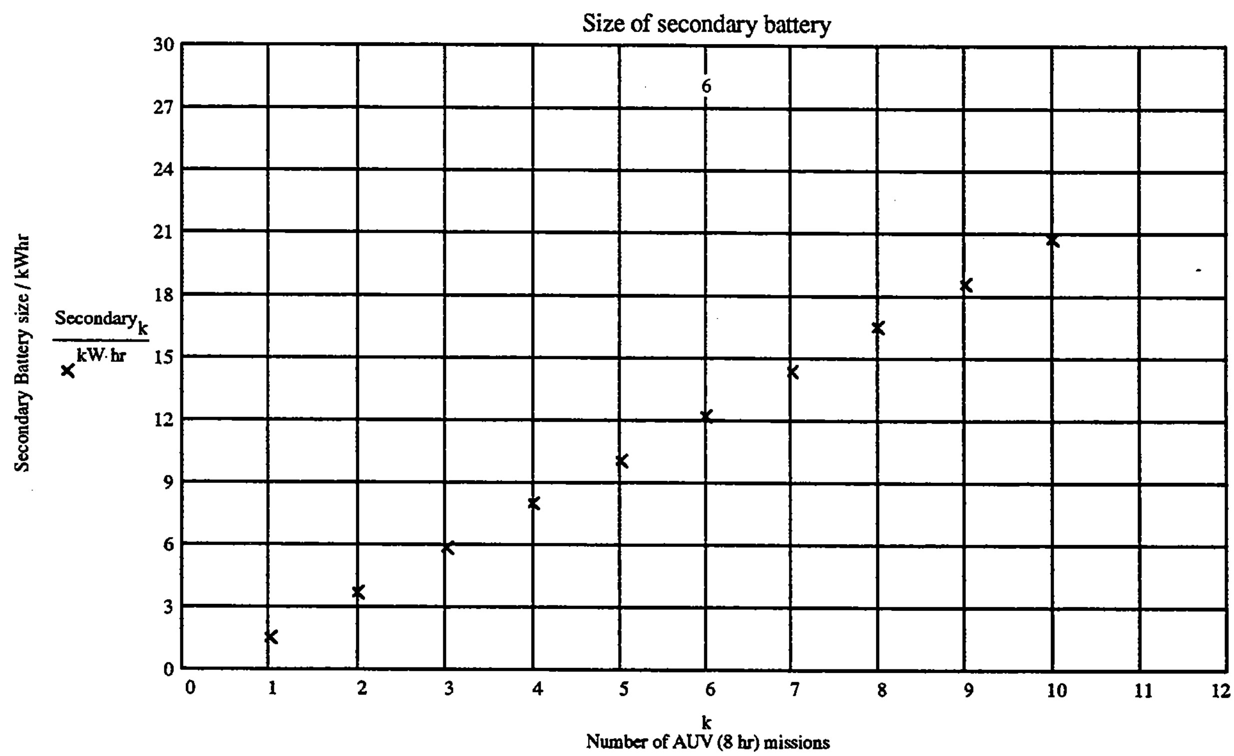
$A_k := T\_miss \cdot k$

event duration $Event := 72 \cdot hr$

$$Secondary_k := ((P\_modem + P\_hotel) - Power) \cdot Event + \frac{P\_auv \cdot A_k}{75 \cdot \% \cdot 80 \cdot \%}$$

Secondary battery size for case A2 $Secondary_6 = 12.195 \cdot kW \cdot hr$

Number of AUV*hr pr Kwhr secondary batt



Calculations on Case B, duty cycle and alternative seawater batteries
Power budget of the Autonomous Oceanographic Sampling Network Moorings

Defenitions:

$nm := 1852 \cdot m$

$km := 1000 \cdot m$

$\rho := 1028 \cdot \frac{kg}{m^3}$

$mon := \frac{1}{12} \cdot yr$

SYSTEM CONFIGURATION

Number of AUV's	$AUV := 6$	
AUV speed	$Vauv := 1.4 \cdot \frac{m}{sec}$	
Number of MOORINGS	$MOR := 3$	
Number of AUV's pr mooring	$N\_AUV\_moo := \frac{AUV}{MOR}$	$N\_AUV\_moo = 2$
Charging efficiency	$Cheff := 80 \cdot \%$	
Transfer efficiency (from mooring to AUV)	$Treff := 75 \cdot \%$	
Total time of experiment	$Time := 5846 \cdot hr$	$Time = 8 \cdot mon$
Maximum mission duration	$T\_miss := 16 \cdot hr$	
Minimum docking time	$T\_dock := 24 \cdot hr$	
Minimum time between events	$T\_rest := 20 \cdot day$	$T\_rest = 0.657 \cdot mon$
Duration of events	$T\_happ := 80 \cdot hr$	$T\_happ = 3.333 \cdot day$

HOTEL LOAD ON EACH MOORING — $Pow\_hot := 10 \cdot watt$

Total energy hotel — $Ener\_hot := Pow\_hot \cdot Time$

$Ener\_hot = 58.46 \cdot kW \cdot hr$

ACOUSTIC MODEM — $Aco\_mod := 20 \cdot watt$

Duty cycle modem — $Aco\_mod\_duty := 50 \cdot \%$

Continous power modem — $Pow\_mod := Aco\_mod \cdot Aco\_mod\_duty$

$Pow\_mod = 10 \cdot watt$

Total energy modem — $Ener\_mod := (Pow\_mod) \cdot Time$

$Ener\_mod = 58.46 \cdot kW \cdot hr$

ODESSEY

$Cd := 0.08 \quad dia := 0.6 \cdot m$

$eff := 40 \cdot \%$

$$Pow\_drag := \frac{\frac{1}{2} \cdot \rho \cdot (Vauv)^2 \cdot \left(\frac{dia}{2}\right)^2 \cdot \pi \cdot Vauv \cdot Cd}{eff}$$

$Pow\_drag = 79.757 \cdot watt$

$Pow\_instr := 80 \cdot watt$

$$Pow\_AUV := \frac{Pow\_drag + Pow\_instr}{Cheff \cdot Treff}$$

$Pow\_AUV = 266.262 \cdot watt$

Duty cycle of AUV

Total number of events

$$N\_happ := ceil\left(\frac{Time}{T\_rest + T\_happ}\right)$$

$N\_happ = 11$

Total number of missions on each happening pr AUV

$$N\_miss\_happ := ceil\left[\frac{T\_happ}{(T\_miss + T\_dock)}\right]$$

$N\_miss\_happ = 2$

Total number of missions pr AUV

$N\_missions := N\_happ \cdot N\_miss\_happ$

$N\_missions = 22$

Total energy used pr AUV

$Ener\_AUV := N\_missions \cdot T\_miss \cdot Pow\_AUV$

$Ener\_AUV = 93.724 \cdot kW \cdot hr$

Travel time pr AUV

$Tauv := N\_missions \cdot T\_miss$

$Tauv = 14.667 \cdot day \qquad Tauv = 352 \cdot hr$

95 kWhr of the energy goes through the secondary battery. The charger efficiency for the secondary battery is in the order of 80%. This gives a total efficiency of SBeff=94%

$SBeff := 94 \cdot \%$

TOTAL energy and average power used pr mooring

$$Power\_mooring := \frac{\frac{Ener\_AUV \cdot N\_AUV\_moo}{Time} \ldots + Pow\_mod + Pow\_hot}{SBeff}$$

Power

$$Power\_mooring = 55.388 \cdot watt$$

$$Power\_overhead := Pow\_mod + Pow\_hot$$

$$Power\_overhead = 20 \cdot watt$$

$$Energy\_mooring := Power\_mooring \cdot Time$$

Energy

$$Energy\_mooring = 323.796 \cdot kW \cdot hr$$

$$Time\_AUV := AUV \cdot N\_missions \cdot T\_miss$$

TOTAL AUV travel time

$$Time\_AUV = 88 \cdot day$$

$$Dist\_AUV := Time\_AUV \cdot Vauv$$

Total AUV traveled distance

$$Dist\_AUV = 1.064 \cdot 10^{4} \cdot km$$

Energy needed under one event

$$Ener\_happ := N\_miss\_happ \cdot T\_miss \cdot N\_AUV\_moo \cdot (Pow\_AUV) \ldots + (Pow\_hot + Aco\_mod) \cdot T\_happ$$

$$Ener\_happ = 19.4 \cdot kW \cdot hr$$

Power needed during event

$$Power\_happ := \frac{Ener\_happ}{T\_happ}$$

$$Power\_happ = 243.01 \cdot watt$$

SEAWATER BATTERY to use with AOSN Case B1
All the numbers are conservative estimates.

Energy needed $Energy := 330 \cdot kW \cdot hr$ $Time := \frac{8}{12} \cdot yr$

Power needed $Avg\_pow := 58 \cdot watt$

Density of magnesium $\rho\_Mg := 1.81 \cdot \frac{kg}{liter}$

Using SSS batteries DIMENSIONS of one CELL

$height := 1 \cdot m$

$diameter := 0.6 \cdot m$

$volume := height \cdot \left(\frac{diameter}{2}\right)^2 \cdot \pi$

$volume = 282.743 \cdot liter$

$anod\_dia := 22 \cdot mm$

$Anod\_nr := 36$

$Cathode\_nr := 12$

Magnesium $Mg\_w := \left(\frac{anod\_dia}{2}\right)^2 \cdot \pi \cdot height \cdot \rho\_Mg \cdot Anod\_nr$

$Mg\_w = 24.769 \cdot kg$

$Pot\_w := 2 \cdot kg$

Total weight of one unit $Cell\_weight := Pot\_w + Mg\_w + 4 \cdot kg$ DC/DC converter weights ca 5 kg/cell

$Cell\_weight = 30.8 \cdot kg$

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

$Power\_cell := 8 \cdot (80 \cdot \%) \cdot watt$ this is from the DC/DC converter

Energy pr cell $Energy\_cell := (40 \cdot kW \cdot hr) \cdot (75 \cdot \%) \cdot 80 \cdot \%$

Number of cells $Cell\_nr := ceil\left[\frac{Energy}{(Energy\_cell)}\right]$ $\frac{Energy}{Time} = 56.469 \cdot watt$

$Cell\_nr = 14$ $volume \cdot Cell\_nr = 3.958 \cdot m^3$

This gives :

Cathodes total number $K\_n := Cell\_nr \cdot Cathode\_nr$

$K\_n = 168$

Total number of anodes	$A\_n := Cell\_nr \cdot Anod\_nr$	
	$A\_n = 504$	
	$Total\_w := Cell\_weight \cdot Cell\_nr$	
Total weight of system	$Total\_w = 431 \cdot kg$	Weight in the water will be less than half
From DC/DC	$Total\_energy := Energy\_cell \cdot Cell\_nr$	
Total energy of battery	$Total\_energy = 336 \cdot kW \cdot hr$	
	$Energy\_density := \frac{Total\_energy}{Total\_w}$	
Energy density	$Energy\_density = 0.78 \cdot \frac{kW \cdot hr}{kg}$	in air energy to the user
	$Total\_volume := volume \cdot Cell\_nr$	
Total volume of battery	$Total\_volume = 3958 \cdot liter$	
	$Volume\_density := \frac{Total\_energy}{Total\_volume}$	
Volume density	$Volume\_density = 84.883 \cdot \frac{watt \cdot hr}{liter}$	

Size of secondary battery is dependent uppon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

$\text{Power} := \text{Power\_cell} \cdot \text{Cell\_nr}$ $\quad k := 0 .. 10$

$\text{Power} = 89.6 \cdot \text{watt}$

Overheads $\text{P\_modem} := 20 \cdot \text{watt}$

$\text{P\_hotel} := 10 \cdot \text{watt}$

AUV $\text{P\_auv} := 160 \cdot \text{watt}$

mission duration $\text{T\_miss} := 16 \cdot \text{hr}$

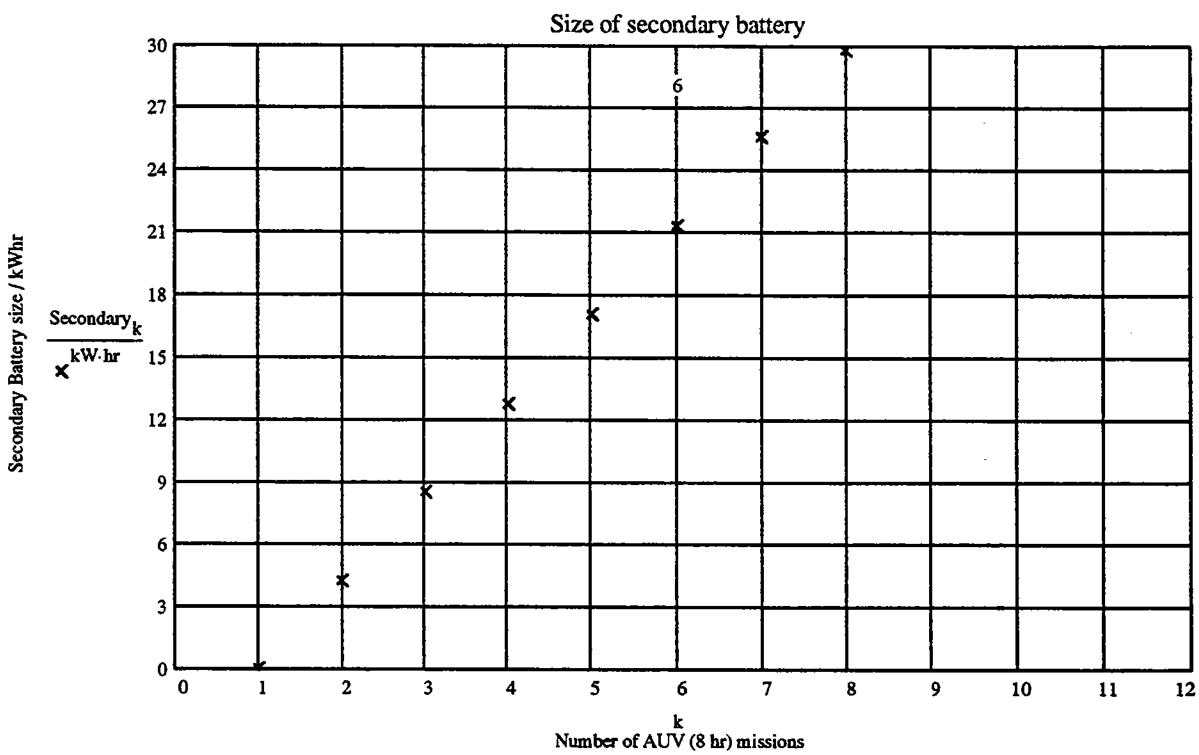
$A_k := \text{T\_miss} \cdot k$

event duration $\text{Event} := 72 \cdot \text{hr}$

$$\text{Secondary}_k := ((\text{P\_modem} + \text{P\_hotel}) - \text{Power}) \cdot \text{Event} + \frac{\text{P\_auv} \cdot A_k}{75 \cdot \% \cdot 80 \cdot \%}$$

Secondary battery size for case B1 $\text{Secondary}_4 = 12.775 \cdot \text{kW} \cdot \text{hr}$

Number of AUV*hr pr Kwhr secondary batt



SEAWATER BATTERY to use with AOSN Case B2
All the numbers are conservative estimates.

Energy needed $Energy := 330 \cdot kW \cdot hr$ $Time := \frac{8}{12} \cdot yr$

Power needed $Avg\_pow := 58 \cdot watt$

Density of magnesium $\rho\_Mg := 1.81 \cdot \frac{kg}{liter}$

Using SSS batteries DIMENSIONS of one CELL

$height := 1 \cdot m$

$diameter := 0.6 \cdot m$

$volume := height \cdot \left(\frac{diameter}{2}\right)^2 \cdot \pi$

$volume = 282.743 \cdot liter$

$anod\_dia := 32 \cdot mm$

$Anod\_nr := 36$

$Cathode\_nr := 12$

Magnesium $Mg\_w := \left(\frac{anod\_dia}{2}\right)^2 \cdot \pi \cdot height \cdot \rho\_Mg \cdot Anod\_nr$

$Mg\_w = 52.405 \cdot kg$

$Pot\_w := 2 \cdot kg$

Total weight of one unit $Cell\_weight := Pot\_w + Mg\_w + 4 \cdot kg$ DC/DC converter weights ca 5 kg/cell

$Cell\_weight = 58.4 \cdot kg$

Maximum power of one unit is assumed to be 2 times power of CFH cell (paper)

$Power\_cell := 8 \cdot 80 \cdot \% \cdot watt$ this is from the DC/DC converter

Energy pr cell $Energy\_cell := 80 \cdot kW \cdot hr \cdot (75 \cdot \%) \cdot 80 \cdot \%$

Number of cells $Cell\_nr := ceil\left[\frac{Energy}{(Energy\_cell)}\right]$ $\frac{Energy}{Time} = 56.469 \cdot watt$

$Cell\_nr = 7$ $volume \cdot Cell\_nr = 1.979 \cdot m^3$

This gives :

Cathodes total number $K\_n := Cell\_nr \cdot Cathode\_nr$

$K\_n = 84$

Total number of anodes	$A\_n := Cell\_nr \cdot Anod\_nr$	
	$A\_n = 252$	
	$Total\_w := Cell\_weight \cdot Cell\_nr$	
Total weight of system	$Total\_w = 409 \cdot kg$	Weight in the water will be less than half
From DC/DC	$Total\_energy := Energy\_cell \cdot Cell\_nr$	
Total energy of battery	$Total\_energy = 336 \cdot kW \cdot hr$	
	$Energy\_density := \frac{Total\_energy}{Total\_w}$	
Energy density	$Energy\_density = 0.822 \cdot \frac{kW \cdot hr}{kg}$	in air energy to the user
	$Total\_volume := volume \cdot Cell\_nr$	
Total volume of battery	$Total\_volume = 1979 \cdot liter$	
	$Volume\_density := \frac{Total\_energy}{Total\_volume}$	
Volume density	$Volume\_density = 169.765 \cdot \frac{watt \cdot hr}{liter}$	

Size of secondary battery is dependent uppon the maximum power from the seawater battery and the number of missions during one event.

Maximum power available:

$\text{Power} := \text{Power\_cell} \cdot \text{Cell\_nr}$ $\qquad$ $k := 0..10$

$\text{Power} = 44.8 \cdot \text{watt}$

Overheads $\quad \text{P\_modem} := 20 \cdot \text{watt}$

$\text{P\_hotel} := 10 \cdot \text{watt}$

AUV $\quad \text{P\_auv} := 160 \cdot \text{watt}$

mission duration $\quad \text{T\_miss} := 16 \cdot \text{hr}$

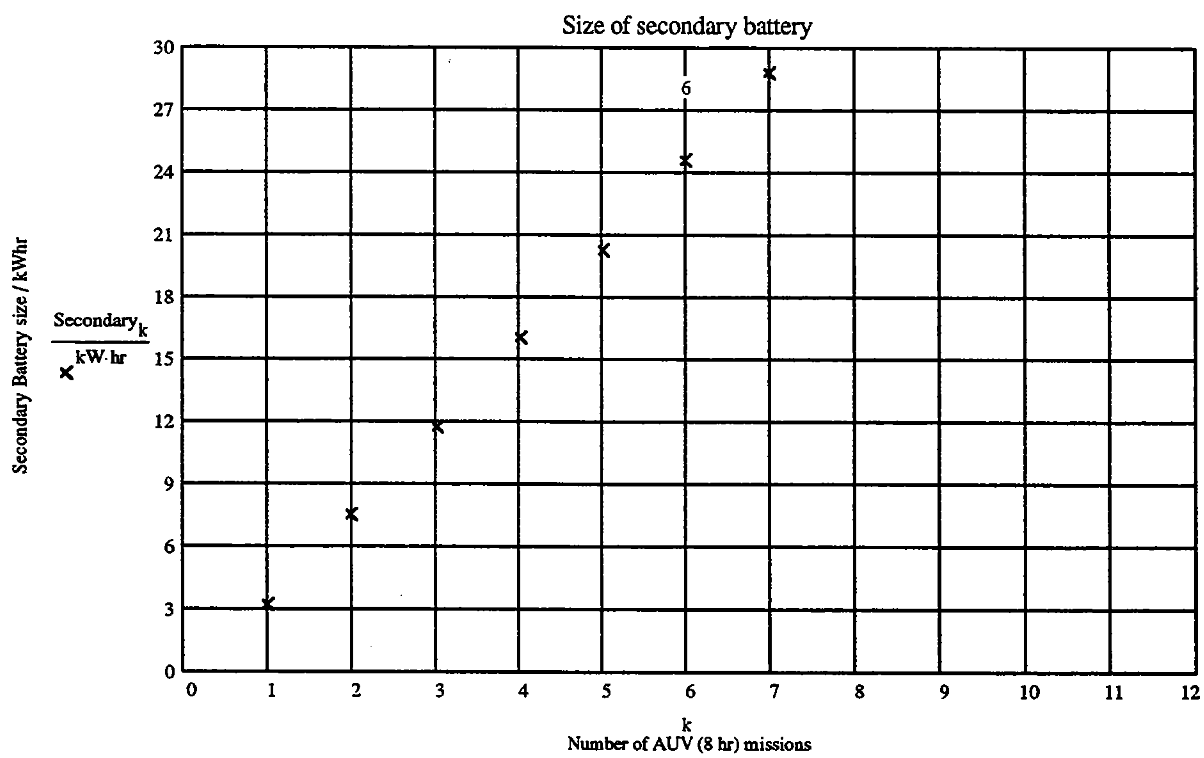
$A_k := \text{T\_miss} \cdot k$

event duration $\quad \text{Event} := 72 \cdot \text{hr}$

$$\text{Secondary}_k := ((\text{P\_modem} + \text{P\_hotel}) - \text{Power}) \cdot \text{Event} + \frac{\text{P\_auv} \cdot A_k}{75 \cdot \% \cdot 80 \cdot \%}$$

Secondary battery size for case B2 $\text{Secondary}_4 = 16.001 \cdot \text{kW} \cdot \text{hr}$

Number of AUV*hr pr Kwhr secondary batt



Typical environmental data from the Labrador sea

GEOSECS ATLANTIC EXPEDITION Vol.1 1972-1973
OXYGEN CONTENT in water collum

STATION: 4 LEG: I POSITION: 54° 5' N 42° 57' W DATE: 30 JUL 72

SAMPLE No.	PRESS DB	DEPTH M	TEMP DEG C	POT TEMP DEG C	SALINITY 0/00	SIGMA θ	SIGMA 2	SIGMA 4	SIGMA Z	OXYGEN μM/KG	SiO_3 μM/KG	PO_4 μM/KG	NO_3 μM/KG	DEPTH M
618	272	270	3.864	3.845	34.851	27.721	36.847	45.541	28.989	285	8.9	1.08	17 1	270
619	322	319	3.895	3.872	34 868	27.732	36.856	45.548	29.231	284	8.9	1 09	17.3	319
620	372	369	3.934	3.907	34.890	27.746	36.868	45.558	29.477	283	9.0	1.09	17.3	369
621	430	426	3.806	3.775	34.872	27.745	36.874	45.571	29.746	287	9.0	1 06	17.1	426
622	498	493	3.761	3.725	34 879	27.755	36.887	45.586	30.071	288	9.0	1.06	17 1	493
623	546	541	3.681	3.622	34 881	27 767	36.904	45.609	30.307	292	9.0	1 07	16.9	541
624	632	626	3.634	3.588	34.866	27.758	36.897	45.604	30.695	293	8.9	1.07	17.1	626
501	756	748	3.725	3.669	34.890	27.769	36.904	45.606	31.276	286	9.5	1.08	17.3	748
502	861	852	3.766	3.701	34.897	27.772	36.904	45.605	31.759	286	9.6	1.08	17.4	852
503	962	952	3.747	3.674	34.910	27 785	36.919	45.620	32.235	285	9.6	1.08	17.3	952
506	1114	1102	3.734	3.648	34.912	27 789	36.924	45.627	32.933	284	9.9	1.09	17.2	1102
504	1115	1103	3.734	3.648	34.910	27 787	36.923	45.626	32.936	284	9.9	1.08	17 4	1103
505	1115	1103	3.734	3.648	34.913	27 790	36.925	45.628	32.938	284	9.9	1.09	17.4	1103
507	1316	1301	3.723	3.620	34.927	27 804	36.940	45.644	33.866	281	10.4	1.10	17.4	1301
508	1466	1449	3 661	3.545	34.939	27.821	36.961	45.668	34.564	279	10.7	1.11	17.4	1449
509	1619	1599	3.593	3.464	34.938	27.828	36.972	45.684	35.265	279	11.2	1.11	17.3	1599
101	1711	1690	3.562	3.425	34.958	27 847	36.994	45.707	35.700	277	11.2	1.12	17.4	1690
510	1772	1750	3.511	3.369	34.945	27.842	36.992	45.708	35.971	278	11.4	1.09	17.7	1750
102	1863	1839	3.466	3.316	34.946	27.848	37.000	45.719	36.388	277	11.6	1.12	17 4	1839
103	1863	1839	3.466	3.316	34.945	27.847	37.000	45.718	36.387	277	11.6	1 12	17.4	1839
511	1919	1894	3.420	3.265	34.958	27.862	37.017	45.738	36.655	277	11.8	1.09	17.6	1894
104	2015	1988	3.379	3.216	34.950	27 861	37.018	45.742	37.085	277	12.0	1.11	17 3	1988
512	2020	1993	3.360	3.197	34.952	27.864	37.023	45.747	37.112	277	12.0	1 09	17.5	1993
105	2114	2086	3.322	3.150	34.956	27.872	37 033	45.760	37 541	278	12.2	1.11	17.2	2086
106	2330	2298	3.184	2.993	34.964	27.892	37 062	45.796	38.532	277	12.8	1 10	17.3	2298
107	2485	2450	3.123	2.918	34.961	27.897	37.070	45.809	39.228	278	13.3	1.10	17.1	2450
108	2485	2450	3.123	2.918	34.966	27.901	37 074	45.812	39.232	278	13.3	1 10	17.0	2450
109	2635	2597	3.058	2.839	34 967	27.909	37.086	45.828	39.907	277	13.7	1.09	16.8	2597
110	2737	2697	3.041	2.812	34.972	27 915	37 094	45.837	40.365	277	13.9	1.09	17.1	2697
111	2837	2794	3.019	2.780	34.974	27 919	37 100	45.845	40.811	277	14.3	1 09	17.1	2794
112	2944	2899	2.971	2.721	34 972	27 923	37.107	45.855	41.288	276	14.9	1.09	17.2	2899
113	3056	3009	2.875	2.616	34.968	27.929	37.119	45.872	41.792	277	15.5	1.10	17.1	3009
115	3157	3107	.2.788	2.520	34.954	27.926	37.121	45.880	42.239	277	15.7	1.10	17.1	3107
116	3260	3208	2.662	2.386	34.943	27.928	37.131	45.897	42.702	279	16.0	1.09	17.1	3208
117	3363	3309	2.587	2.302	34.937	27.930	37.138	45.908	43.160	280	15.9	1.08	17.1	3309
118	3471	3414	2.538	2.242	34.932	27 931	37.142	45.915	43 635	281	15.9	1 07	16.9	3414
119	3510	3452	2.536	2.236	34.933	27.933	37.144	45.917	43.806	281	16.1	1 07	16.8	3452
120	3530	3472	2.535	2.233	34.932	27.932	37 143	45.917	43.892	281	16.1	1.07	17.0	3472
121	3550	3491	2.537	2.232	34.932	27.932	37 143	45.917	43.979	281	16.0	1.07	17.0	3491
122	3560	3501	2.532	2.226	34.927	27.928	37.140	45.914	44.020	281	16.1	1.06	16.9	3501
123	3569	3510	2.525	2.219	34.933	27.934	37.146	45.920	44 065	281	16.3	1.07	16.9	3510
124	3580	3520	2.525	2.217	34.931	27.932	37 145	45.919	44 111	281	16.4	1.07	16.8	3520

BOTTOM DEPTH FOR CAST 1 IS 3528

Typical environmental data from the Labrador sea
GEOSECS ATLANTIC EXPEDITION Vol.1 1972-1973
AVERAGE WATER CURRENT in water collum

Labrador Current

The Labrador Current flows close to the Continental Shelf along the coast of Labrador at speeds from 0.2 to 0.5 knot; it is augmented by the current flowing out of Hudson Strait. Part of the Labrador Current flows southwest along the U. S. coast to about 36°N during the winter months; it usually extends farther south nearer to Cape Hatteras during the summer.

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16. Abstract (Limit: 200 words)

The Autonomous Oceanographic Network (AOSN) Labrador Sea Experiment (LSE) will be held in the Labrador Sea at a seawater depth of 3000 – 3500 meters. The total system will consist of a number of AUVs which will operate from a set of moorings within a defined area. Each mooring will be placed on the seafloor. The docking stations will be placed in the water column at 1000 – 2000 meters water depth. Each AUV will have at least one possible docking station to charge batteries and to transfer data. This report will show two different load pattern examples for the AOSN LSE, and the implications upon the power budget of the mooring.

The possible use of a seawater battery and its implications upon the system will be discussed. A preliminary design of the sizes and weights of a seawater battery for this application is also included. Energy delivery to an experiment like the AOSN LSE with the use of a seawater battery is feasible both technically and within the time span of the AOSN project. The environment of the Labrador Sea is well documented and seems suitable to accomodate a seawater battery. Due to the large water depths involved and the simplicity of the system, and the lack of any large pressure housings the seawater battery seems like a good candidate both in respect to costs and feasibility.

17. Document Analysis a. Descriptors

recharging of AUVs
seawater battery
typical power budget for AOSN

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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